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S.L. Smith, M.M. Burgess, and F.M. Nixon

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Authors' address

S.L. Smith (ssmith@nrcan.gc.ca)
M.M. Burgess (mburgess@nrcan.gc.ca)
F.M. Nixon (mnixon@nrcan.gc.ca)
Terrain Sciences Division
Geological Survey of Canada
601 Booth Street
Ottawa, Ontario K1A 0E8

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Abstract: Active-layer and permafrost temperature data collected in the Mackenzie Delta, at Canadian Forces Station Alert and Baker Lake have been analyzed along with climatic data to determine the response of the active layer and the ground thermal regime to the anomalous warming associated with strong El Niño conditions of 1998. In the Mackenzie Delta region, early warming in 1998 resulted in earlier thaw of the active layer, warmer summer ground temperatures, and a longer thaw season which produced greater thaw penetration compared to previous years in the 1990s. At Baker Lake, warming was less pronounced and occurred later in the summer resulting in a slight extension of the thaw season into the fall. Warming was less extreme in the high Arctic but snow depths were greater at CFS Alert in 1998 and this appears to have resulted in higher shallow ground temperatures during the winter (February to April) of 1998.

Résumé : Des données sur la température de la couche active et du pergélisol collectées dans le delta du Mackenzie, à la station des Forces canadiennes Alert et à Baker Lake ont été analysées en parallèle avec des données climatiques afin de connaître la réaction de la couche active et du régime thermique du sol au réchauffement anomal attribuable au puissant effet El Niño de 1998. Dans la région du delta du Mackenzie, le réchauffement précoce de 1998 a entraîné un dégel plus hâtif de la couche active, une augmentation des températures du sol en été et une période de dégel plus longue, de sorte que le front de dégel a atteint en 1998 des profondeurs plus grandes qu'à n'importe quel autre moment de cette décennie. À Baker Lake, le réchauffement a été moins important et s'est produit plus tard au cours de l'été, ce qui a prolongé légèrement la saison de dégel jusqu'en automne. Le réchauffement a été moins marqué dans le Haut-Arctique, mais la couche de neige plus épaisse à la station des Forces canadiennes Alert en 1998 aurait fait monter les températures près de la surface du sol durant l'hiver (février à avril) de 1998.

INTRODUCTION

Strong El Niño conditions in 1998 resulted in the warmest year on record in Canada since 1948 (Environment Canada, online; <http://www.msc-smc.ec.gc.ca/ccrm/bulletin>). A great deal of spatial variability in both the timing and the magnitude of this warming was apparent across the Canadian Arctic. For example, mean annual air temperatures were about 5°C above the 1961–1990 normal in the Mackenzie Delta region of the western Arctic but only about 2°C and 2.5°C above normal at CFS Alert and Baker Lake respectively (Fig. 1). Seasonal variation in the magnitude of the warming anomalies was also observed. In the western Arctic, the largest warming anomalies occurred in the winter and spring of 1998. In the region west of Hudson Bay and in the high Arctic, however,

pronounced warming anomalies were observed in the summer and fall seasons. Warming in 1998 started in the western Arctic and then progressed to the north and east and diminished in strength.

Short-term warming can have significant impacts on the permafrost environment. Increases in ground temperature, changes in thaw-penetration and active-layer (the upper layer of the ground that thaws in summer) thickness may occur affecting landscape processes and increasing related hazard potentials such as terrain and slope instability (Dyke et al., 1997; Dyke and Brooks, 2000). This can have significant implications for the stability of existing infrastructure and future development in northern regions. The response of the ground thermal regime to changes in air temperature is dependent on site characteristics such as vegetation, surficial materials, and moisture content in addition to other climatic parameters such as snow cover which modulate the exchange of heat between the air and the ground. Extremes in air temperature therefore will not necessarily result in extremes in ground temperature. The response of the permafrost environment to warming in 1998 was examined by the Geological Survey of Canada (GSC) as part of a project led by Environment Canada and Natural Resources Canada and funded by the Government of Canada's Climate Change Action Fund (CCAF) to document the state of the Arctic cryosphere during the extreme warm summer of 1998.

The GSC has been monitoring active-layer conditions and permafrost temperatures at numerous sites in the Mackenzie Delta region throughout the 1990s. Data collected from these sites were analyzed along with climatic data to determine the response of the active layer and the ground thermal regime to the anomalous warming of 1998. The results from the Mackenzie Delta are briefly compared to the results from Baker Lake and CFS Alert to determine the regional variability in the permafrost response. The focus of this analysis is on the timing, duration, and spatial variability of the response of the active layer and ground temperatures.

MACKENZIE DELTA REGION

The GSC active-layer monitoring network, established in the 1990s, consists of 60 sites in the Mackenzie region (Nixon and Taylor, 1998; Nixon, 2000), where active-layer thickness has been determined from measurements of maximum summer thaw penetration obtained using thaw tubes (Mackay, 1973). About 40 of these sites are located in the Mackenzie Delta–Tuktoyaktuk Peninsula region of which 14 have air and ground temperature sensors which utilize single-channel mini loggers to continuously record data at 3–6 hour intervals. Air-temperature sensors are placed in a radiation shield mounted 1.5 m above the ground surface. A similar temperature sensor is buried at a nominal depth of 3–7 cm to measure near-surface ground temperature. Data from nine sites (Fig. 2), having the most extensive and complete temperature records, are presented in this paper.

Active-layer thicknesses determined at the nine sites between 1991 and 1999 are shown in Figure 3a. Significant interannual variation in active-layer thickness is observed at

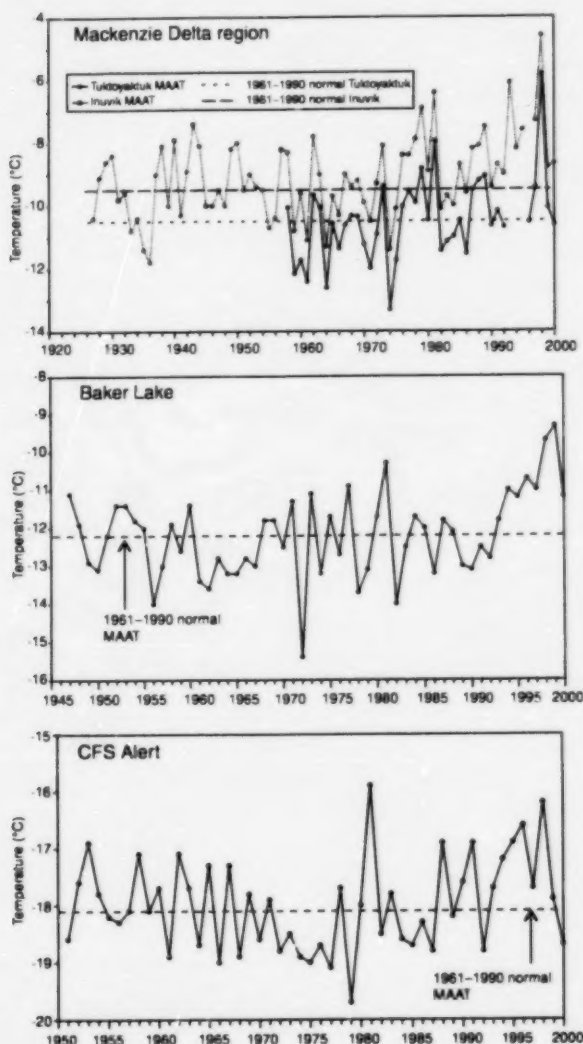


Figure 1. Mean annual air temperature (MAAT) for the Mackenzie Delta region, Baker Lake, and CFS Alert. Data from Environment Canada (2000).

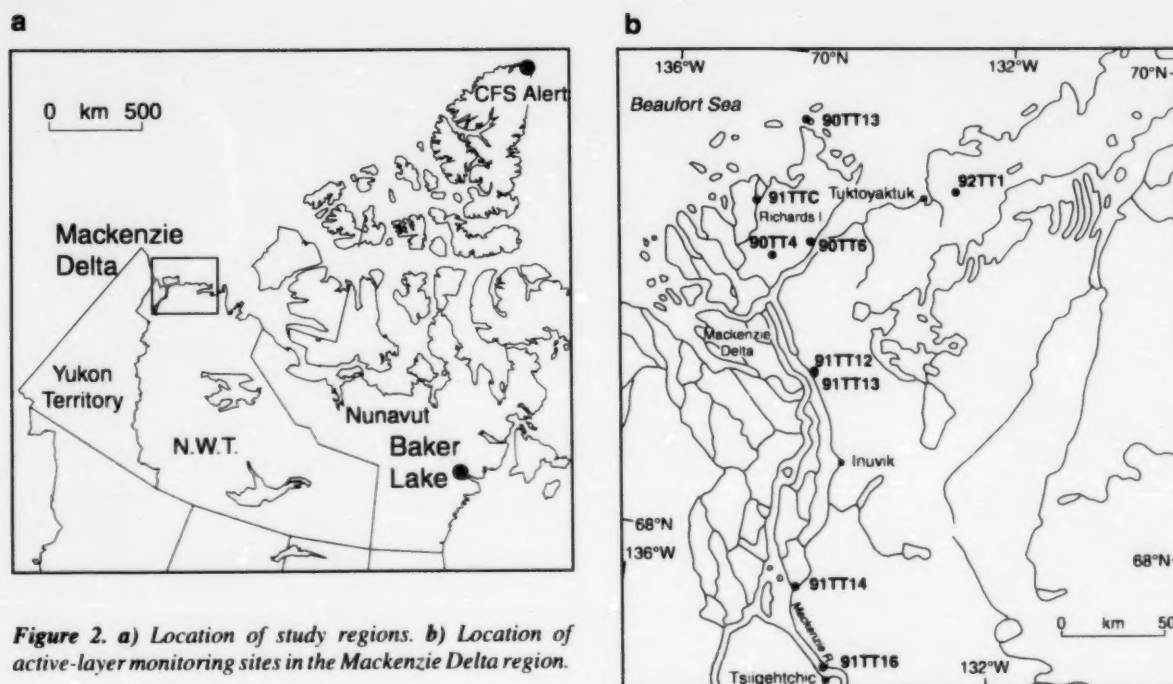


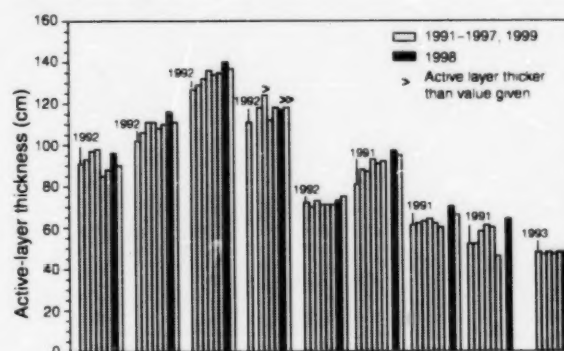
Figure 2. a) Location of study regions. b) Location of active-layer monitoring sites in the Mackenzie Delta region.

Figure 3. a) Active-layer thickness and b) maximum summer thaw penetration determined for nine sites in the Mackenzie Delta-Tuktoyaktuk Peninsula region between 1991 and 1999. Thaw penetration is measured relative to a fixed point above the ground surface. A ">" symbol indicates that thaw depth was greater than the maximum value that could be determined by the thaw-tube installation.

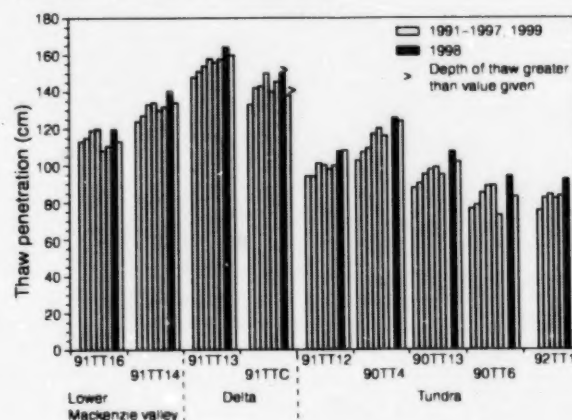
some of the sites, and the thickest active layers were generally observed in 1998. At two sites (91TT12 and 92TT1), however, there is little variation in active-layer thickness over the monitoring period.

For ice-rich material, significant settlement of the ground surface may occur as the seasonal thaw depth increases. Maximum annual thaw penetration measured relative to a fixed point above the ground surface (Fig. 3b) will therefore give a better indication of the annual variation of thaw penetration (Nixon and Taylor, 1998). At sites with fine-grained, ice-rich surficial material, such as Involut hill (92TT1), a large increase in thaw penetration occurred in 1998 which was also accompanied by significant ground subsidence and hence very little change in active-layer thickness (Fig. 4a). Changes in active-layer thickness, however, tend to closely track those of annual thaw penetration at sites which have surficial material containing little excess ice and subject to very little surface settlement upon thawing. At Tsiigehtchic (91TT16) for example, the large increase in thaw penetration in 1998 produced very little settlement of the ground surface (Fig. 4b) and therefore the active-layer thickness also increased significantly. The use of thaw penetration eliminates local

a Active-layer thickness



b Maximum summer thaw penetration



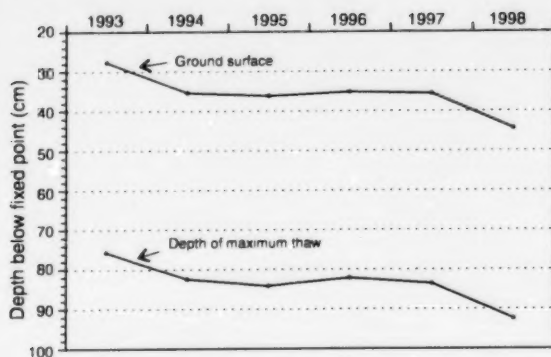
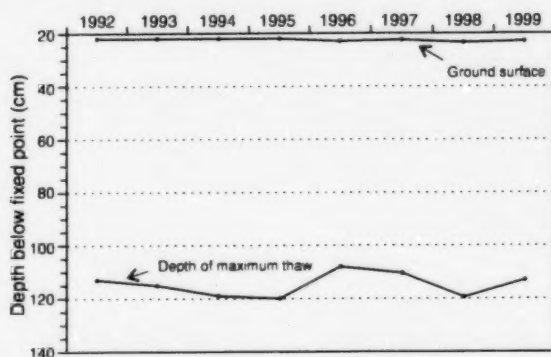
a Involute hill 92TT1**b** Tsiigehtchic 91TT16

Figure 4. Maximum summer thaw penetration and position of ground surface at time of maximum thaw for **a**) Involute hill and **b**) Tsiigehtchic. The Involute hill site is located at the top of a low cuesta collapse form in thermokarst terrain and the soil consists of 20 cm of organic material over well drained, silty clay till. The Tsiigehtchic site is on an alluvial surface on the Mackenzie Delta. At this site, 15 cm of silty litter overlie well drained, organic silt. Medium sand is found about 70 cm below the surface.

complexities associated with ground-ice melting and soil compaction, and allows a better comparison of interannual thaw between sites (Nixon and Taylor, 1998).

Thaw penetration data generally show an increasing trend between 1991 and 1998. Wolfe et al. (2000) found that thaw penetration in 1998 for eight sites in northern-central Richards Island and two sites on the Tuktoyaktuk Peninsula was 12–23 cm greater than in 1991 or 1992 and that ground subsidence exceeded that recorded in previous years by 1–7 cm. Thaw penetration for the nine sites considered in this paper (Fig. 3b) was, depending on the site, up to 11–23 cm greater in 1998 than the lowest values observed during the rest of the monitoring period.

Records of daily air temperature from the nine sites indicate that during 1998, both late winter (February onwards) and summer temperatures were higher than in previous years. Summer ground-surface temperatures were generally higher in 1998 although the magnitude was dependent on the site. At a few sites, 1998 winter (December 1997 to February 1998) ground surface temperatures were higher than previous years but at most sites they were similar to those of other years. Air temperatures in 1998 rose above 0°C earlier in the spring than previously observed, leading to warmer ground-surface temperatures and earlier thaw of the active layer as illustrated by site 91TT13 in Figure 5. This resulted in an extension of the thaw season that, depending on the site, was from 8–25 days longer than that of previous years in the decade. For the sites examined, mean annual ground-surface temperatures ranged from 1–4°C higher in 1998 than in earlier years during the monitoring period. The ground-surface thawing degree day index was up to 50–90% greater in 1998 than previous years. Warmer active-layer temperatures and longer thaw periods promoted greater thaw penetration in 1998 compared to earlier years. Air temperatures in this region (Fig. 1, 5) declined in 1999 to values similar to those recorded earlier in the decade. At most sites, a decrease in thaw penetration (Fig. 3) accompanied the cooler conditions in 1999.

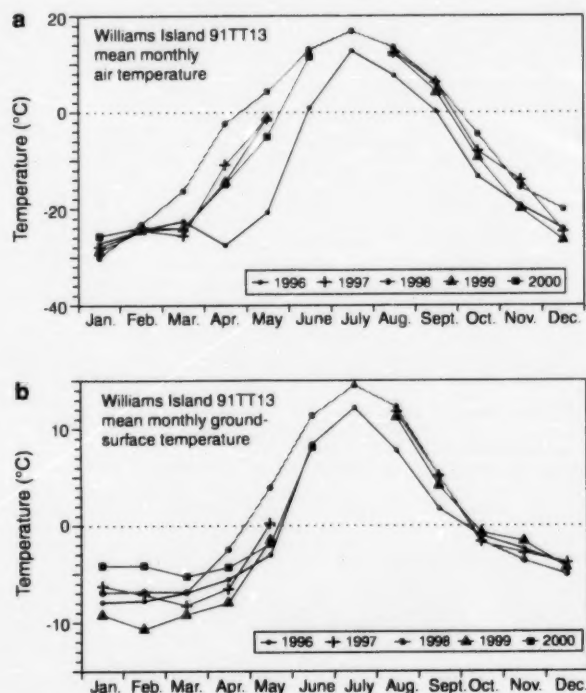


Figure 5. Mean monthly **a**) air and **b**) ground-surface temperature between 1996 and 2000 for a monitoring site at Williams Island (91TT13), north of Inuvik, Northwest Territories.

Other 'unusual' periods have been identified in the air and ground-surface temperature records for this region. Environment Canada air-temperature records show that 1996 was one of the coldest years of the 1990s at Tuktoyaktuk (Fig. 1) and data from the monitoring sites indicate that the summer of 1996 was colder than those of other years during the monitoring period (Fig. 5a). Thawing of the ground was delayed in the spring and summer ground-surface temperatures were generally lower than in other years (Fig. 5b). Freezing of the active layer also occurred earlier in the fall of 1996. The shorter thaw season resulted in less thaw penetration in 1996 compared to 1995 (Fig. 3b). Ground-surface temperatures in the winter and early spring of 2000 (January to March) were observed to be higher at some sites than that observed during the rest of the monitoring period (Fig. 5b). Air temperatures during this period, however, were not higher than those observed during 1998, suggesting that other factors such as an increase in snow cover might be partially responsible for the interannual variability in winter ground temperatures.

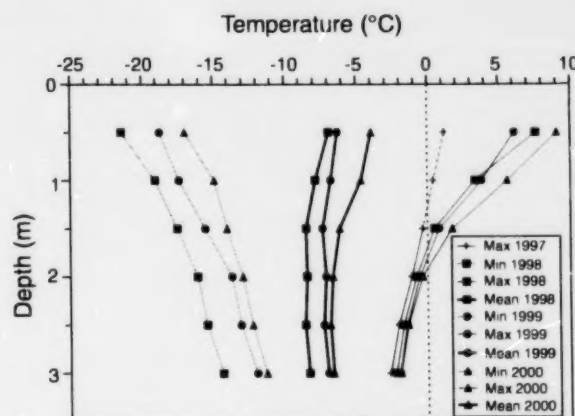
BAKER LAKE

Ground temperatures to a depth of 3 m have been measured at Baker Lake, Nunavut ($64^{\circ}10'N$, $95^{\circ}30'W$; see Fig. 2 for location) in a collaborative project (involving GSC, Environment Canada, University of Toronto, and Orin Durey) since the fall of 1997. Data are recorded manually on a monthly to semi-monthly basis. An increasing trend in mean annual ground temperatures has been observed throughout the monitoring period (Fig. 6a), with larger increases in temperature occurring in the winter compared to summer. Maximum summer thaw depths have continued to increase since 1997 (Fig. 6b) with the largest increase occurring in 1998. Winter ground temperature in 1998 at a depth of 0.5 m, was $2-3^{\circ}C$ lower than that recorded in 1999 and 2000 (Fig. 7). Summer ground temperatures recorded for the same depth in 1998 were about $1^{\circ}C$ higher than that recorded for 1999; however, maximum summer temperature at this depth was about $1.4^{\circ}C$ higher in 2000 than 1998.

Low winter air temperatures in 1998 compared to later years in the record were accompanied by lower winter ground temperatures (Fig. 7). Snow cover at this site is generally less than 10 cm thick and the variation in shallow ground temperature during the winter tends to follow that of the air temperature. Only late summer and fall (August–November) air temperatures were anomalously warm in 1998. Air temperatures remained warm during the fall of 1998 and freezing of the active layer was delayed (Fig. 7). Warmer ground temperatures in the late summer and early fall and the extension of the thaw season by about two weeks resulted in greater thaw penetration in 1998 compared to the previous year.

The aspect of the ground-temperature record at this site that stands out is the overall warming of winter ground temperatures (Fig. 6, 7) during the monitoring period rather than the ground warming in the summer of 1998. It is also important to note that according to Environment Canada air temperature records (Fig. 1), 1999 was warmer than 1998. Monthly air temperatures for January to April 1999 were up to $7^{\circ}C$

a Ground temperature



b Maximum summer thaw depth

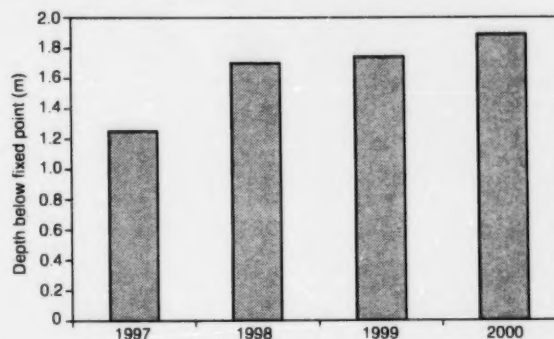


Figure 6. a) Annual maximum, minimum, and mean ground temperatures for 1997 to 2000 at a monitoring site at Baker Lake, Nunavut. Only maximum ground temperatures are plotted for 1997 since temperature monitoring began in September 1997. The maximum values in 1997 for the upper two sensors were probably not captured in the record and this part of the profile is shown by a dashed line. b) Maximum summer thaw penetration (measured from a fixed point) for 1997 to 2000. Note that the maximum thaw depth for 1997 may not have been captured in the data record.

higher than those in 1998 and these warmer air temperatures are associated with higher winter ground temperatures during 1999 compared to 1998.

CANADIAN FORCES STATION ALERT

Permafrost temperatures have been measured to depths of 60 m since 1978 by the GSC in five boreholes at Canadian Forces Station Alert, Nunavut ($82^{\circ}30'N$, $62^{\circ}25'W$; see Fig. 2 for location) with the ongoing collaboration of the Department of National Defence. The frequency of data acquisition in the 1990s ranged from monthly at shallow (15 m)

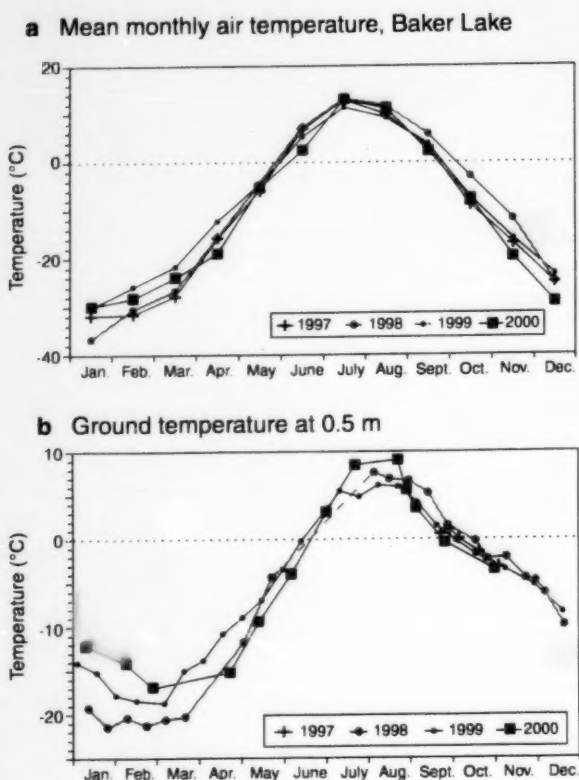


Figure 7. a) Mean monthly air temperatures (Environment Canada, 2000) recorded at the Environment Canada weather station, Baker Lake for 1997–2000. b) Ground temperatures measured at a depth of 0.5 m at a monitoring site at Baker Lake between 1997 and 2000.

boreholes to quarterly at deeper (60 m) boreholes; however, data are only available for the first half of 1998 due to a gap in data collection related to federal downsizing of the monitoring program. Funding for two years was obtained from the CCAF in 1999 to re-activate the monitoring program, process data collected over the last 10 years, and undertake an analysis of the complete data set.

Higher shallow ground temperatures were observed at CFS Alert in the winter months of 1998 (February to April) even though winter air temperatures (measured at Environment Canada weather station) were similar to those recorded during the rest of the decade (Fig. 8). Snow cover is generally thin (less than 20 cm) to absent in this area, but exhibits high spatial and temporal variability (Fig. 9) and is an important factor influencing the response of shallow permafrost temperatures to changes in air temperature. Snow depths measured at the borehole sites during the winter of 1997–1998 were much greater than in previous years. At one of the boreholes for example, maximum winter snow depth was generally less than 20 cm throughout the monitoring period but in 1998 it was greater than 50 cm (Fig. 9). The deeper snow pack provided additional insulation resulting in a lower rate of heat

loss from the ground during the winter. Limited summer data suggest that the presence of a thick snow cover for a longer duration may, however, have delayed the onset of active-layer development and warming of the ground in the summer.

No active-layer data are available for the CFS Alert monitoring sites. Probing is not possible because of the coarse surface materials and there are no thaw-tube installations. The first sensor on the temperature cables is within the permafrost

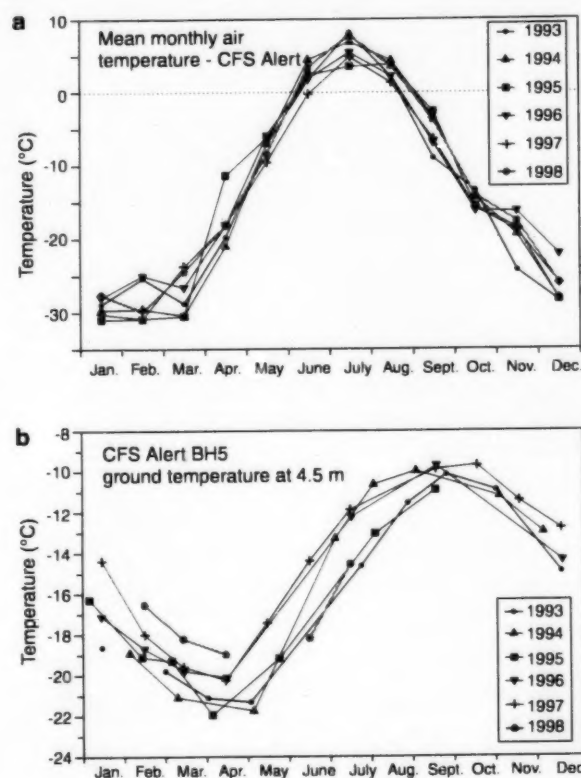


Figure 8. a) Mean monthly air temperature at Environment Canada weather station at CFS Alert for 1993–1998. b) Ground temperatures measured between 1993 and 1998 at a depth of 4.5 m in a borehole at CFS Alert.

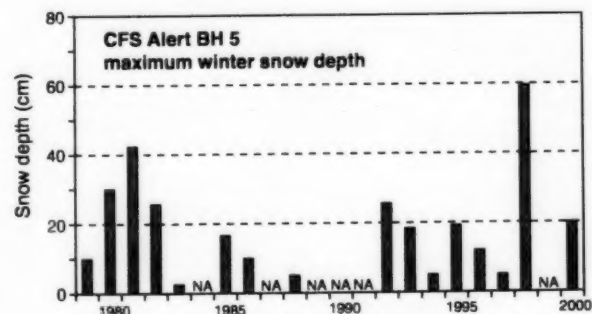


Figure 9. Maximum winter snow depth recorded at CFS Alert borehole 5.

(depth varies from site to site but the shallowest sensor is at a depth of 0.76 m) and thus the active-layer thickness is less than 0.76 m. In summer of 2000, data loggers and air and ground-surface temperature sensors were installed. Analysis of air and ground-surface temperature data together with higher frequency permafrost temperature data should enable better estimates of active-layer thickness as well as a better understanding of the local microclimate and its role in influencing the permafrost response to changes in air temperature.

Environment Canada air temperature records (Fig. 1) indicate that 1981 not 1998 was the warmest year on record since 1951 at CFS Alert. Analysis of the annual and seasonal air temperature, permafrost temperature, and snow-depth data during the early 1980s may provide a better evaluation of the impact of short-term warming on the permafrost thermal regime at a high Arctic location.

SUMMARY

In the winter and spring of 1998, a major warm anomaly was located over the western Arctic which moved east and northward while diminishing in strength through the summer, and was situated over the Arctic Islands in the fall. This pattern is reflected in the active-layer conditions and ground thermal regime of two of the three study locations examined in this paper. In the Mackenzie Delta region the early warming resulted in earlier thaw of the active layer and a longer thaw season that led to greater thaw penetration during the summer of 1998. At most of the sites examined, the increase in thaw penetration was also accompanied by greater active-layer thickness in 1998. Thaw depths generally increased between 1991 and 1998, with maximum values observed in 1998. Thaw depths in 1999, however, were generally less than those in 1998 as air temperatures declined to values similar to those earlier in the decade. At Baker Lake, temperature increases were less pronounced and were delayed until later in the summer, thus the summer thaw season extended slightly into the fall. Insufficient data are available for CFS Alert to evaluate the impact of autumn warming on the permafrost thermal regime. Warming in the high Arctic was less extreme than that in the western Arctic, but changes in other climatic parameters such as snow depth were important. This is reflected in the shallow permafrost thermal regime at CFS Alert which experienced the warmest winter temperatures in 1998.

Summer ground-surface temperatures in the Mackenzie Delta region were warmer in 1998 than other years during the monitoring period but for some sites winter ground temperatures were warmest in 2000. Air temperatures during winter 2000, however, were not unusually warm which suggests that other factors (e.g. variations in snow cover) are responsible for these warmer winter ground-surface temperatures.

The analysis for the Mackenzie Delta region considered only near-surface ground (active layer) temperature; deeper permafrost temperatures have not been examined. Permafrost temperatures to depths of 30 m have been measured over the last decade at a number of sites in this region. Analysis of

these data is required to fully assess the impact of short-term warming on the permafrost thermal regime in the Mackenzie Delta.

A general warming trend during the late 1990s is observed in the ground temperature record at Baker Lake. At both Baker Lake and CFS Alert, 1998 was not the warmest year on record. Higher mean annual air temperatures were recorded during 1999 and 1981 for Baker Lake and CFS Alert respectively.

This study illustrates the importance of examining both the seasonal and annual variability of the air temperature regimes, as well as site characteristics and ancillary climate parameters, such as snow cover, in order to facilitate a better characterization and understanding of the spatial and temporal variability in the permafrost response to climate change in the Canadian Arctic. The data presented in this paper suggest that there was considerable regional variability in the timing and magnitude of the permafrost response to the short-term warming observed in 1998.

ACKNOWLEDGMENTS

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